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## **Permanent Participating FRP Formwork for Concrete Floor Slabs**

Xian Gai, Antony Darby, Tim Ibell and Mark Evernden

**Synopsis:** This paper presents a new concept for an FRP-Concrete composite floor system. The system consists of a moulded glass fibre reinforced polymer (GFRP) grating adhesively bonded to rectangular pultruded GFRP box sections as structural formwork for a concrete slab. Holes cut into the top flange of the box sections at a variable spacing allow concrete 'studs' to form at the grating/box interface. During casting, GFRP dowels are inserted into the holes to further connect the grating and box sections.

Following preliminary component tests on two concrete blocks, experimental results show that the concrete filled grating provides a 100% increase in strain capacity when compared to a plain concrete block. It is therefore feasible to provide ductility to the complete system through the concrete in compression. Four push-out GFRP grating-box section specimens were then tested in double shear to assess the shear behaviour of the proposed GFRP dowel shear connector in both partially concrete-filled and fully concrete-filled box sections. From the resulting load-slip curves, a progressive longitudinal shear failure was seen to be provided by such a connection. The experimental results indicate that this type of shear connection can provide robustness and reasonable ductility to the system. Research is now underway to test a complete prototype system under variable load conditions to examine whether the behaviour is as predicted.

**Keywords:** Fibre reinforced polymer, GFRP dowels, moulded GFRP grating, pultruded GFRP box sections, permanent participating formwork.

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## INTRODUCTION

FRP permanent participating formwork, also referred to as a stay-in-place (SIP) system, remains structurally integrated with the concrete and provides structural strength to the overall system. The formwork not only acts as self-supporting formwork during construction, but also acts as external, durable, structural reinforcement, with the combined structural system making appropriate use of the FRP in tension and the concrete in compression. The system has the benefit of simplifying the construction process, with no laying of reinforcement required, thus reducing construction time as well as increasing durability in corrosive environments.

In the past few decades the use of fibre reinforced polymers (FRPs) for the retrofitting and strengthening of existing structures has been widely used in the construction industry. Within the new build sector, there has been a significant interest in the use of FRP hybrid system in concrete decks and slabs. A number of hybrid FRP-Concrete systems have been developed, where FRP materials are used as a structurally integrated stay-in-place formwork for concrete.

One of the first hybrid concepts to make use of shear connection systems, as proposed by Descovic et al. (1995), consists of a rectangular GFRP filament wound box section with an upper layer of concrete and a thin layer of CFRP bonded to the lower flange. An epoxy adhesive was applied to connect the GFRP flange and the concrete. Experiments

showed that steel bolts improved the longitudinal shear behaviour at the GFRP-concrete interface. Moreover, the section showed a pseudo-ductile behaviour by progressive failure of its different components.

Hall and Mottram (1998) combined a GFRP pultruded section (two upstands fixed to a continuous base used for floor panels) with concrete. The concrete was either directly cast onto the FRP panels or onto an intermediate epoxy adhesive layer that was not yet cured. Four-point bending tests demonstrated that the adhesive bonded interface improved the performance of the beams, although they failed by shear in the concrete due to a lack of shear reinforcement.

Further research on hollow FRP box sections with a thin concrete top layer, similar to those originally proposed by Descovic et al. (1995), was performed by Canning et al. (1999) and Huallat et al. (2003). The investigation of different configurations of hybrid beams showed that the best method of ensuring full composite action between the FRP and the concrete was to apply fresh concrete onto a water-based adhesive. The failure mechanism in this case was concrete crushing and local buckling of the FRP component. However, it was realized that this bonding technique is impractical on site. Therefore, a more practical and robust mechanical interlock mechanism is required.

Research in this field by Keller et al. (2007) utilized pultruded FRP planks with T-upstands as shuttering for concrete. These T-shape longitudinal ribs not only increased the section stiffness when compared to a flat sheet, but also served as an embedded mechanical anchor at the FRP/concrete interface. However, visible and excessive slip was detected at the end support due to lack of confinement in the transverse direction. To overcome this shortcoming, Dieter et al. (2002) and Bank et al. (2006) developed a three-dimensional modular bi-directional grating system to confine the concrete in both directions. The failure mechanism, due to punching shear, occurred at the lap joints and was still sudden and without warning.

Fam et al. (2005) developed and tested rectangular concrete-filled filament-wound GFRP tubes in flexure, and later Fam and Skutezky (2006) added a thin concrete layer on the top of the concrete-filled pultruded rectangular GFRP tubes, mechanically bonded using GFRP dowels embedded into the tubes. The author studied the effects of concrete filling of the tubes, length of shear span, and CFRP lamination of the GFRP tension flange. The experiments demonstrated that dowels used in the concrete-filled GFRP tube-slab system provide more slip resistance and more composite action than those used in the hollow GFRP tube-slab system, and that the concrete fill has a substantial effect on initial stiffness but a small effect on strength. However, this changes the failure mode from shear failure of GFRP dowels to rupture of GFRP tension flange, which is sudden and brittle.

The reviewed research shows a high potential for hybrid FRP-concrete construction where the FRP is utilized in tension and the concrete is utilized in compression. Each of the developed systems shows its own advantages and disadvantages. The main problems that occurred were FRP hollow section web buckling, lack of ductility of the overall system, insufficient shear transfer between the FRP and concrete to maintain full

composite action, and a complicated manufacturing process which is impractical for most applications. The novel hybrid FRP-Concrete floor system proposed in this paper provides a potential solution to some of these problems.

In this paper, the concept of concrete filled GFRP box beams is taken a step further, by adding a concrete filled GFRP moulded grating acting compositely with two GFRP box sections. The composite action is achieved by using GFRP dowels combined with concrete studs formed along the grating/box section interface. This composite system is mainly designed as a one-way spanning floor system for building construction. Experiments on composite slabs will be reported to demonstrate the feasibility of the proposed system. A particular objective is to evaluate two types of failure mode, either by controlled concrete crushing or longitudinal shear failure, and to assess the provision of ductility in the overall system.

#### RESEARCH SIGNIFICANCE

The lack of ductility, which can result in the potential for sudden and unexpected failure, is the key concern for using FRP permanent formwork in practice. Investigating the means to achieve a robust bond between the FRP and concrete, leading to a ductile failure is, thus, crucial. This research presents a novel mechanical shear connector along the Concrete-FRP interface and a concrete filled FRP grating in the compression zone to enhance the strain capacity in the concrete. Overcoming the issue of lack of ductility in an FRP/concrete system will lead to the development of a new form of construction which has potential advantages compared to conventional slab construction.

#### FRP PERMANENT PARTICIPATING FORMWORK DESCRIPTON

The proposed FRP formwork is a composite structure consisting of two layers of different materials: pultruded hollow GFRP box section for the tension and moulded GFRP grating filled with concrete for the compression, as shown in Figure 1. FRP materials are inherently non-ductile, so other means of providing progressive failure of the system are required. Thus, to provide ductility, the concrete in compression is utilised. Mass concrete has minimal ductility, but by utilizing an FRP moulded grating filled with concrete in the compression zone, the concrete is confined, allowing much greater strain capacity to be developed and hence increasing overall ductility.

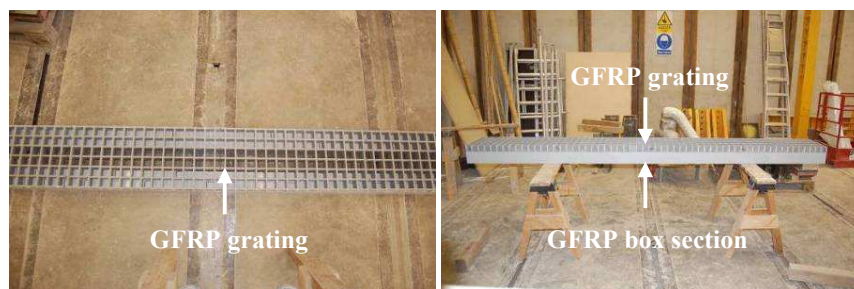


Figure 1 – Proposed FRP formwork system

The requirement to provide a robust connection between the GFRP box section in tension and the concrete in compression is addressed by using GFRP dowels embedded into the concrete as shown in Figure 2.

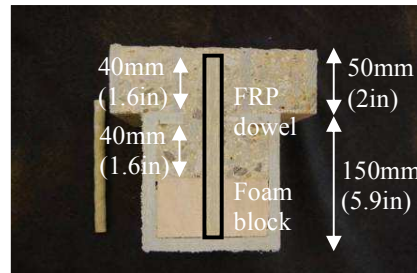


Figure 2 – GFRP dowels embedded in to concrete

This study will examine the failure mechanism of both fully composite and partially composite FRP-Concrete hybrid slabs in order to verify whether its corresponding failure mode (concrete crushing failure or longitudinal shear failure at the grating/box section interface) can provide sufficient ductility to the overall system.

#### EXPERIMENTAL PROGRAM

Four push-out tests were used to assess the robustness of the proposed shear connectors and its load-slip behaviour. Two compression tests were used to assess the confining effect of moulded GFRP grating on strain capacity of concrete. Based on the findings of both component tests, three slab tests were designed to study the overall performance of the proposed FRP-Concrete composite system and its ductility.

##### Material properties

In this study, pultruded GFRP box sections, GFRP dowels, foam blocks, moulded GFRP grating and concrete were used as shown in Figure 3. The following sections provide a detailed description of the different materials.



Figure 3 – GFRP dowels, moulded GFRP grating, foam block, and GFRP box section.  
(From left to right)

GFRP box sections – Commercially available GFRP pultruded box section [100 x 100 x 8mm (4 x 4 x 0.3in)] supplied by Fibreline Composites, Denmark, were used as the tension component. The longitudinal roving and multidirectional mats provide

longitudinal and transverse strength and stiffness. The box section had a tensile strength of 240MPa (35ksi) and an Elastic modulus of 23GPa (3336ksi) [values obtained by the manufacturer according to European Standard EN 13706].

GFRP dowels – Aslan 100 GFRP pultruded rebar of 10mm diameter, composed of E-glass fibres of minimum 70% fibre content by weight and vinylester resin, were supplied by Hughes Brothers and were used as GFRP dowels in this study. The sand coated bars have an ultimate tensile strength, elastic modulus and shear strength of 760MPa (110ksi), 40.8GPa (5917ksi), and 152MPa (22ksi) respectively (values obtained by the manufacturer according to ACI-440).

Moulded GFRP grating – Commercially available panels of Moulded GFRP grating [50 x 50mm (2 x 2in) grid size] were cut into 300 x 3000mm (11.8in x 9.8ft) strips for fabrication of the slab specimens. The grating (shown in Figure 4), which was 50mm (2in) thick with a 35-40% fibre volume fraction, has a tensile strength and elastic modulus of 172MPa (25ksi) and 15GPa (2175ksi) respectively.



Figure 4 – Commercial available moulded GFRP grating

Self-flowing concrete – super-plasticizer was used in order to make the concrete more expandable and self-flowing, allowing the concrete to easily fill the small holes without excessive compaction.

#### Description and fabrication of test specimens

Push-out test specimens – Two push-out test specimens ( $P_1$  and  $P_2$ ) were initially tested to compare the load-slip response of GFRP dowels embedded in partially concrete-filled GFRP box sections ( $P_1$ ) with those embedded in fully concrete-filled GFRP box sections ( $P_2$ ). Both specimens consisted of two 450mm (17.7in) long GFRP box sections bonded back to back using a two part epoxy adhesive (Araldite 2015). These were then connected on both sides to a 150 x 50 x 400mm (6 x 2 x 15.7in) moulded GFRP grating [grid size = 50 x 50mm (2 x 2 in), thickness of individual bars = 8mm (0.3in)] using the same epoxy adhesive. 42 mm (1.6in) diameter holes were drilled into the top flange of the GFRP box sections to allow the concrete studs to form at the grating/box section interface, as shown in Figure 5 (a).

In specimen  $P_1$ , an 84mm (3.3in) [width] x 44mm (1.7in) [depth] foam block was inserted into the hollow GFRP box sections in order to hold the GFRP dowels in place, as shown in Figure 5 (b). Thus, the concrete filled depth in the box section was only 40mm (1.6in). Four sand-coated GFRP dowels [diameter 10mm (0.4in)] were manually pushed

into the foam block with an upstand of 88mm (3.5in) and longitudinal spacing of 100mm (4in) centre to centre, as shown in Figure 5(c). In specimen  $P_2$ , although no foam block was used and the whole box section was filled with concrete, the same lengths of GFRP dowel [40mm (1.6in)] were inserted into the concrete as found in specimen  $P_1$ .

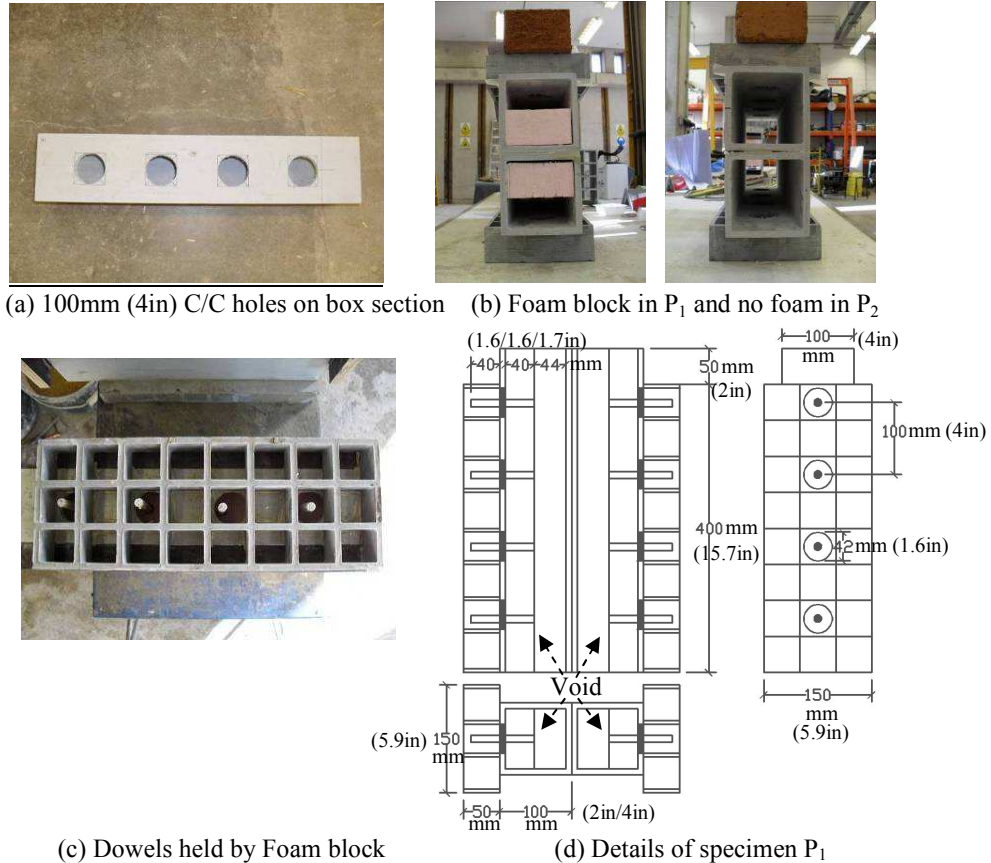


Figure 5 – Push-out specimens  $P_1$  and  $P_2$

Following the initial testing, push-out specimens  $P_3$  and  $P_4$  were designed and tested to compare the load-slip response of four GFRP dowels ( $P_3$ ) with eight GFRP dowels ( $P_4$ ) embedded in a partially concrete-filled GFRP box section. The fabrication procedure was exactly the same as for specimen  $P_1$ , although the distribution of shear connectors in  $P_3$  and  $P_4$  was in a 'zig-zag' pattern rather than the straight line seen in  $P_1$ , as illustrated in Figure 6(a,b). Shear connectors were longitudinally spaced at 200mm (7.9in) centre to centre in specimen  $P_3$  and 100mm (4in) centre to centre in specimen  $P_4$ , with a transverse spacing of 50mm (2in) used in both, as shown in Figure 6(c). The diameter of the hole was reduced from 42mm (1.6in) in  $P_1$  to 38mm (1.5in) in  $P_3$  and  $P_4$  due to space limitations dictated by the width of the flange, Figure 6 (d).



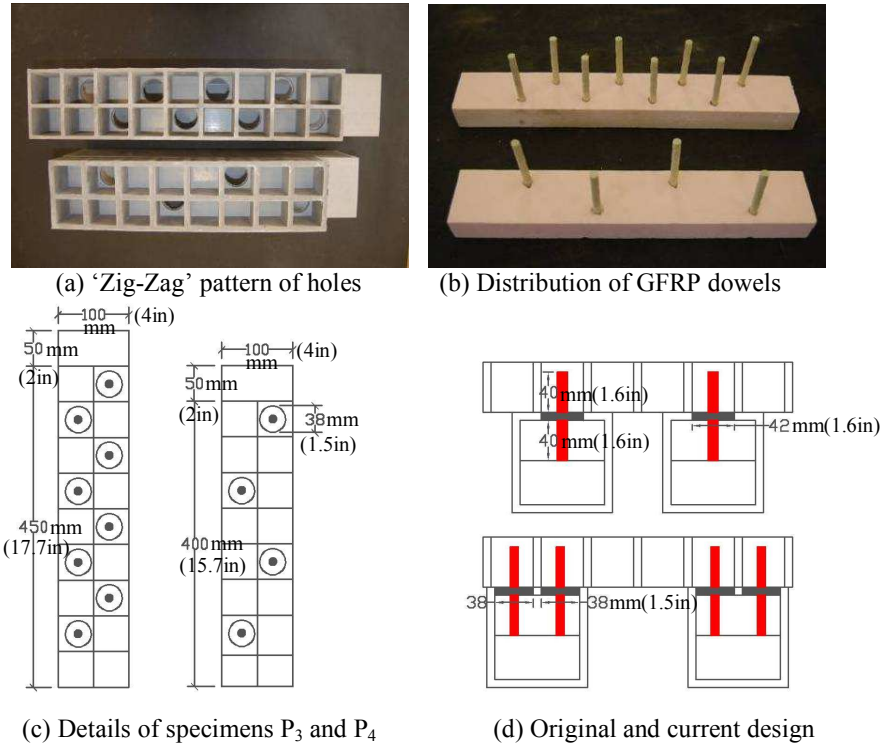


Figure 6 – Push-out specimens P<sub>3</sub> and P<sub>4</sub>

**Concrete block specimens** – The concept of utilizing the moulded GFRP grating to confine the concrete in the compression zone in order to introduce the ductility through controlled concrete crushing was investigated by comparing a plain concrete block with a concrete filled grid block in compression, Figure 7. The concrete filled grid block was fabricated by bonding two pieces of 50 x 100 x 200mm (2 x 4 x 7.9in) grating back to back in order to achieve a 100 x 100mm (4 x 4in) square loading section, which is identical to the plain concrete block. The grids were then filled with concrete to reach the same level as the grating.

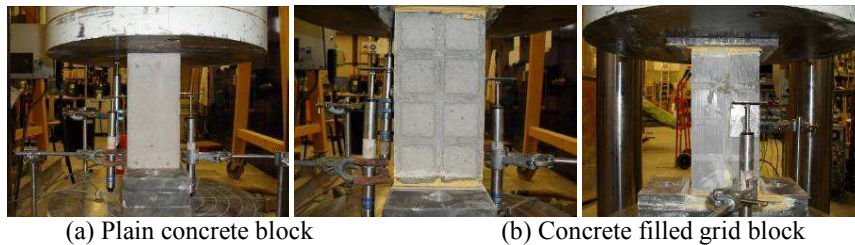


Figure 7 – Concrete block specimens

#### Test setups and instrumentations

Push-out specimens – Push-out specimens were loaded using a 2000kN (450kip) Dartec machine at a constant rate of 0.3mm/min (0.012in/min). Three pairs of LVDTs were used to measure the relative slip between the concrete-filled grating and the GFRP box section, as shown in Figure 8. The average concrete cube strength in  $P_1$  and  $P_2$  is 43MPa (6.2ksi) on one side and 52MPa (7.5ksi) on the other side. The average concrete cube strength in  $P_3$  and  $P_4$  is 35MPa (5.1ksi) on both sides at the time of testing.



Figure 8 – Push-out tests set-up

Concrete block specimens – Concrete block specimens were loaded using a 2000kN (450kip) Dartec machine at a constant rate of 0.3mm/min (0.012in/min). One pair of LVDTs was used to measure the displacement of the specimen from the middle on both sides, as shown previously in Figure 7. The average cube strength was 52MPa (7.5ksi) at the time of testing.

### EXPERIMENT RESULTS AND ANALYSIS

#### Push-out Specimens

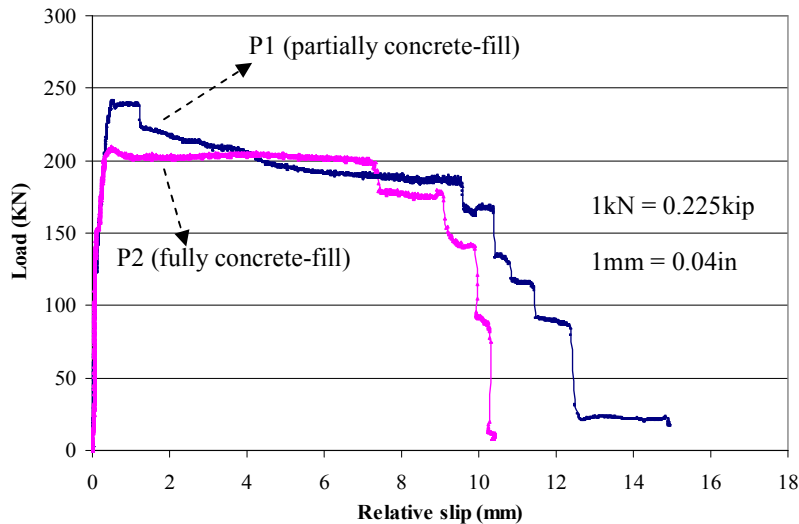


Figure 9 – Load versus Relative slip graph of push-out specimens  $P_1$  and  $P_2$

Push-out specimens  $P_1$  and  $P_2$  – Figure 9 shows that the load-slip behaviour is quite similar in both specimens  $P_1$  (partially filled) and specimen  $P_2$  (fully filled) at any given load. Both specimens had an extremely high initial stiffness provided by the concrete studs across the grating/box section interface, as shown in Figure 10, followed by a plastic plateau as the embedded GFRP dowels began to carry the shear. The shear load reached a maximum of approximately 240kN (54kip) in  $P_1$  and 213kN (48kip) in  $P_2$ , provided by the GFRP dowels acting in tension and shear along the concrete failure plane. GFRP dowels fractured due to excessive slip, which occurred at approximately 10mm (0.4in) in  $P_1$  and 7mm (0.3in) in  $P_2$ .

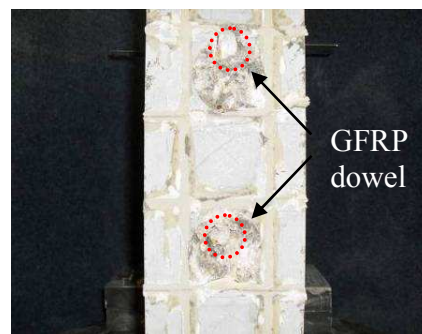


Figure 10 – Shear off of the GFRP dowels and concrete studs

The experimental results demonstrate that there is no significant difference between specimens  $P_1$  and  $P_2$  with identical embedded length of FRP dowels [40mm (1.6in)] in terms of load-slip response and ultimate shear capacity. It is then clear that the main function of the concrete fill in the box section is to provide support for the GFRP dowels through embedment within the concrete fill. Partially concrete-filled sections can reduce the immediate deflection in the construction stage as unnecessary concrete in the box sections is removed. More importantly, the foam block provides a holder for the GFRP dowels, thus simplify the construction process. For these reasons the partially filled construction method was adopted for subsequent push-out tests and slab tests.

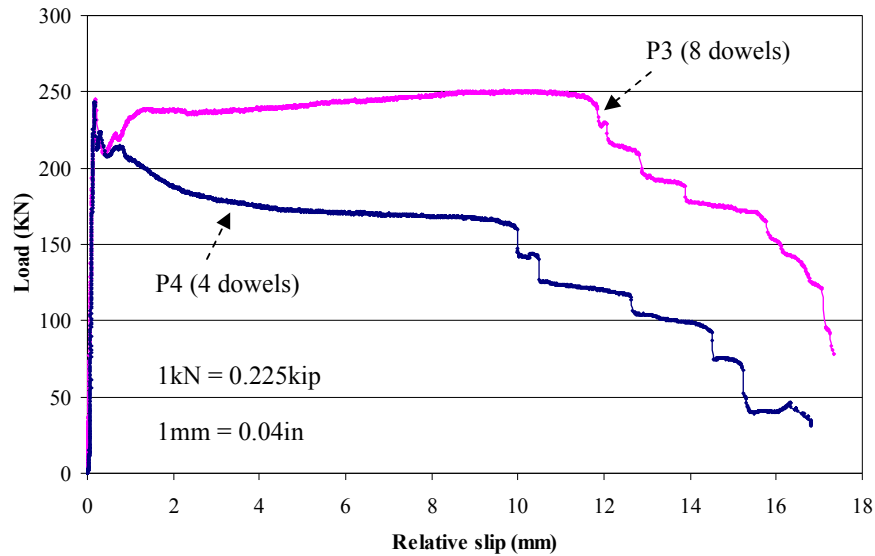


Figure 11 – Load versus Relative slip graph of push-out specimens P<sub>3</sub> and P<sub>4</sub>

Push-out specimens P<sub>3</sub> and P<sub>4</sub> – Figure 11 shows that both specimens P<sub>3</sub> (8 dowels) and P<sub>4</sub> (4 dowels) had an extremely high stiffness and the shear load in both reached a maximum of 240kN (54kip). Following this, the shear load in P<sub>3</sub> gradually dropped to 170kN (38kip) and maintained this level. Conversely, the shear load in P<sub>4</sub> dropped initially by 30kN (6.7kip) and recovered to its original peak of 240kN (54kip) at 1mm (0.04in) relative slip. The GFRP dowels fractured at approximately 12mm (0.5in) for specimens P<sub>3</sub> and 10mm (0.4in) for specimen P<sub>4</sub>.

Specimen	No. of shear connectors	Cube strength of concrete [MPa(ksi)] Left/Right side	Diameter of concrete studs [mm(in)]	Pattern of shear connectors	Concrete fill	Peak load [kN(kip)]	Plastic capacity [kN(kip)]	Ultimate Slip [mm(in)]
P <sub>1</sub>	4	43(6.2)/52(7.5)	42(1.7)	Straight	Partial	240(54)	190(43)	10(0.4)
P <sub>2</sub>	4	43(6.2)/52(7.5)	42(1.7)	Straight	Full	213(48)	200(45)	7(0.3)
P <sub>3</sub>	8	35(5.1)/35(5.1)	38(1.5)	Zig-zag	Partial	245(55)	240(54)	12(0.5)
P <sub>4</sub>	4	35(5.1)/35(5.1)	38(1.5)	Zig-zag	Partial	241(54)	170(38)	10(0.4)

Table 1 – Comparison of push-out specimen P<sub>1</sub>, P<sub>2</sub>, P<sub>3</sub> and P<sub>4</sub>.

Push-out test results (Table 1) demonstrate that there was a small drop of 10% in plastic capacity [20kN (4.5kip)] by changing the pattern of the GFRP dowels from a straight line (P<sub>1</sub>) to a zig-zag (P<sub>4</sub>). However, the ultimate slip at fracture of the GFRP dowels was identical in both P<sub>1</sub> and P<sub>4</sub>. It can also be seen that in the zig-zag arrangement doubling the number of GFRP dowels results in a 40% increase in plastic capacity (P<sub>3</sub> and P<sub>4</sub>). However, it is also clear that there was a negligible difference in peak failure caused by

changing the number of GFRP dowels combined with concrete studs. It can be concluded that when comparing specimens  $P_1$  and  $P_4$ , the peak load is determined by adhesion both between the concrete-FRP interface and the glued FRP-FRP interface. Furthermore, the plastic capacity is shown to mainly depend on the shear resistance and tensile resistance of GFRP dowels and a progressive failure mechanism can be achieved.

Concrete block specimens – The plain concrete block failed due to concrete crushing with little ductility, while the concrete filled grid block failed due to concrete crushing around the grid cells and longitudinal splitting of the fibres in a much more gradual manner, as shown in Figure 12.



Figure 12 – Failure of block specimens

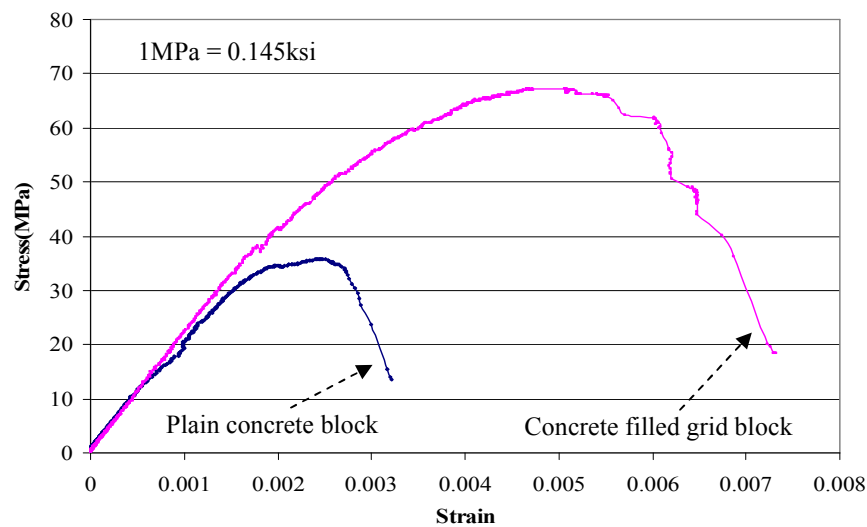


Figure 13 – Stress-strain graph comparing the plain concrete and concreted filled grating compression tests.

As shown in Figure 13, the concrete confined by the FRP grating led to a 100% increase in ultimate compressive strength, and a 100% increase in ultimate strain capacity

compared to an identically sized plain concrete specimen. The dramatic increase in compressive strain demonstrates that the grid structure of moulded GFRP grating confines the concrete effectively due to its bi-directional fibre orientations, resulting in significant deformability. Thus, it might be possible to utilize the increase in concrete strain capacity to provide ductility to the overall system through the concrete in compression.

#### Conclusions and summary

1. The concrete filled grating specimen greatly increases the ultimate compressive stress and strain capacity compared to the plain concrete specimen. By utilizing the increased strain capacity, a favourable failure criterion in controlled concrete crushing might create ductility in the overall system.

2. The combination of concrete studs formed at the concrete/FRP interface and GFRP dowels anchored at both sides of the interface provide a robust shear connection in the joint, which create a progressive longitudinal shear failure.

3. The load-slip characteristic of partially concrete-fill specimen ( $P_1$ ) and fully concrete-fill specimen ( $P_2$ ) are similar, this demonstrated that the main function of the concrete fill in GFRP box sections is to provide support for GFRP dowels.

4. In the zig-zag arrangement of shear connectors, doubling the number of GFRP dowels results in an increase of 40% in plastic capacity ( $P_3$  and  $P_4$ ).

The component tests described above demonstrate the potential for achieving both ductility and a robust interaction between the permanent participating FRP formwork and the concrete.

#### ONGOING AND FUTURE WORK

Following the findings of the preliminary tests, research is now underway to test the complete system at a large scale under various loading conditions to examine whether the ductility provided by either concrete crushing or longitudinal shear failure can be achieved in the prototype system. These tests and predictions of their moment-curvature behaviour are made below.

#### Slab specimens

The prototype slab specimens are composed of two 3m (9.8ft) long GFRP box sections [100 x 100 x 8mm (4 x 4 x 0.3in) adhesively bonded to 300mm wide, 3m long moulded GFRP grating using Araldite 2015, as shown in Figure 14. Both components are connected at a variable spacing using 88mm (3.5in) long sand-coated GFRP dowels [diameter 10mm (0.4in)] embedded into the concrete. 38mm (1.5in) diameter holes are drilled on the top flange of the box sections in order to push the GFRP dowels into the 44mm (1.7in) thick foam block and allow the concrete to fill the remaining 40mm (1.6in) of the box section. Once the concrete is cured, 38mm (1.5in) diameter concrete studs are formed around these holes to provide the necessary support for the GFRP dowels through embedment in the concrete fill. The composite action of two components during the concrete casting initially relies on the adhesive bond. After settlement of the concrete,

the GFRP dowels and concrete studs act compositely to resist longitudinal shear between the concrete and GFRP box sections.

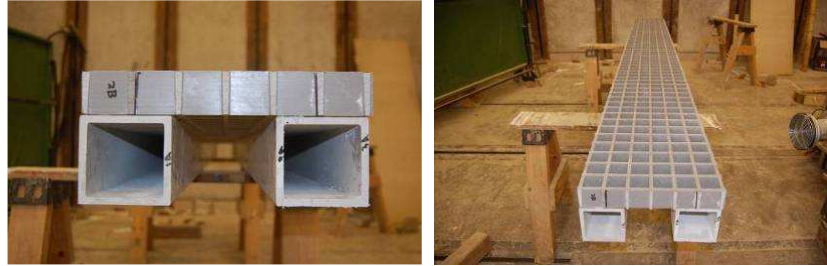


Figure 14 – Details of the slab specimens

#### Analytical model

Linear elastic analysis and rigid plastic analysis models are used below to predict the failure behaviour of the slab specimens with a longitudinal shear failure criterion:

Deric John Oehlers' Rigid-plastic analysis – Oehlers and Sved (1995) developed an analytical approach for an idealized composite beam in which the steel and concrete components remain linear-elastic but the shear connector component (steel stud) is fully plastic. This procedure is developed by extending Newmark's (1951) linear elastic work by allowing the plasticity and the finite ductility of shear connectors, but can be also applied to FRP-Concrete composite system as the load-slip characteristics of GFRP dowels combined with concrete studs is similar to steel studs.

In rigid-plastic analysis, it will be assumed that the FRP box sections and concrete elements are linear-elastic throughout the length of the beam and the shear connectors are fully plastic throughout, i.e., the elastic region near mid-span will be ignored, and hence all the connectors have the load-slip characteristic determined from push-out tests shown in Figure 15.

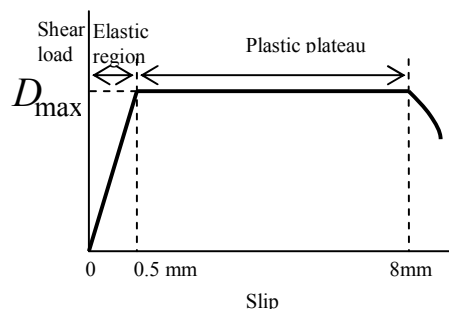


Figure 15 – Load-slip characteristic of the proposed shear connector

### Slab test loading configuration

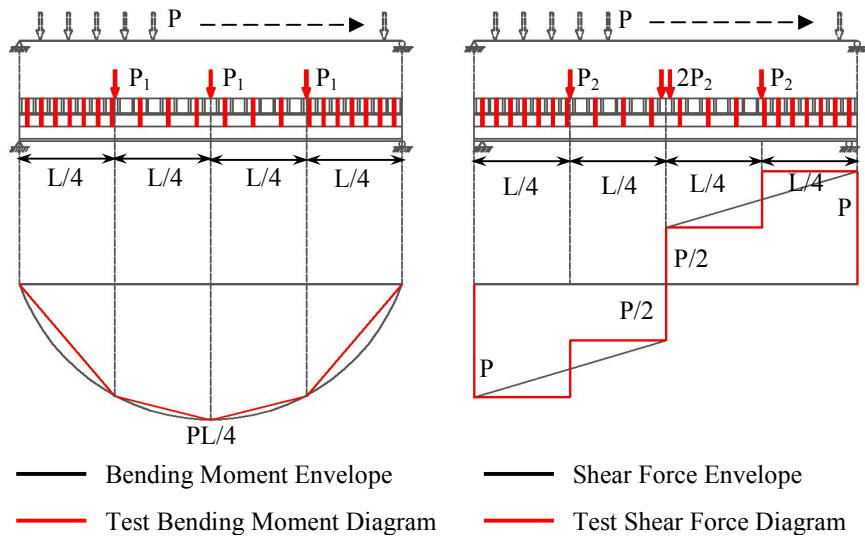


Figure 16 – Bending moment envelope, shear force envelope, and corresponding simulated loading configuration

Three slab specimens will be tested in five-point bending. The first slab specimens ( $S_1$ ) will be tested with three equal single point loads,  $P_1$ , acting at the quarter span, mid-span and three quarters span as illustrated in Figure 16. This loading configuration is to simulate the bending moment envelope, which is caused by a single point load moving along the span from one support to the other.  $S_1$  is designed with full composite action until failure as a result of concrete crushing. This is designed to verify the concept of utilizing the extra strain capacity gained from the concrete filled grating to provide ductility to the overall system when subjected to bending and shear.

The second and third slab specimens ( $S_2$  and  $S_3$ ) will be tested with two single point loads acting at the quarter span and three quarters span and two single point loads acting at the mid-span, as illustrated in Figure 16. This loading configuration is to simulate the shear force envelope caused by a single point load moving along the span from one support to the other.  $S_2$  is designed with 60% degree of composite action and is designed to fail due to either concrete crushing or by fracturing of the shear connectors.  $S_3$  is designed with 30% degree of composite action and is designed to fail due to fracturing of the shear connectors only. The objective of both tests is to verify the concept of utilizing the post yielding characteristic of the proposed shear connector (GFRP dowels embedded within the concrete) to provide ductility to the overall system.



The moment-curvature response of three slab specimens has been predicted using the elastic and rigid plastic analysis as described previously (shown below in Figure 17).

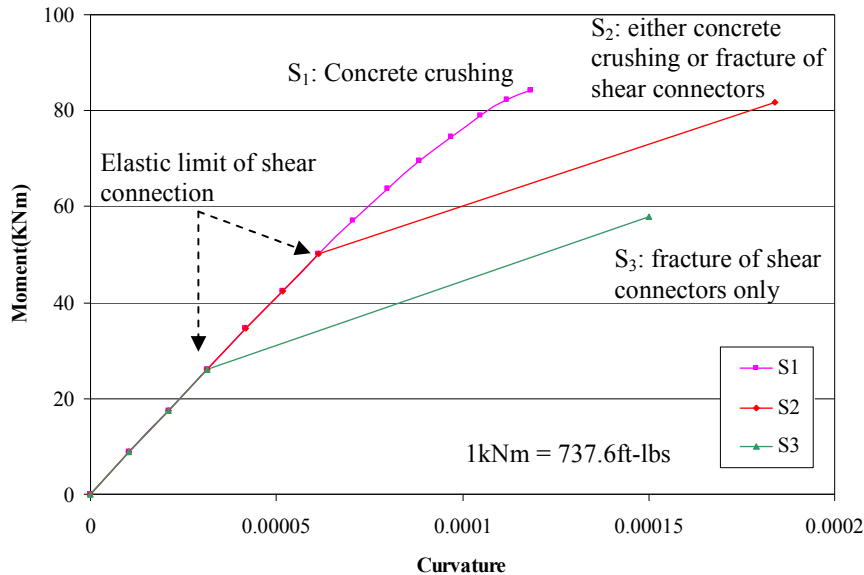


Figure 17 – Moment versus Curvature graph predicted for three slab specimens ( $S_1$ ,  $S_2$ ,  $S_3$ ) using elastic and rigid plastic analysis

#### Conclusion and summary

From the predicted moment-curvature curves, it is proposed that specimens with incomplete shear connections will fail by progressive longitudinal shear failure, providing reasonable ductility to the overall system. This prediction will be assessed at a later date against experiment results, and comparisons between theory and reality presented at the conference.

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